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MATERIALS RESEARCH FOR HEAT TRANSFER FLUIDS

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Midwest Research Institute

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NOTICES

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FOREWORD

This report was prepared by the Midwest Research Institute, 425 Volker Boulevard, Kansas City, Missouri 64110, under USAF Contract No. AF 33(657)-10295, Phase II. The contract was initiated under Project No. 7343, "Aerospace Lubricants," Task No. 734302, "Solid Lubricant Development," and Project No. 7340, "Non-Metallic Composite Materials," Task No. 734008, "Power Transmission - Heat Transfer Fluids and Other Forms of Energy Transfer Fluids." The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, with Mr. R. J. Benzing, MANL, acting as project engineer.

This technical report covers the work conducted from June 1964 through June 1965. The manuscript was released by the author in December 1965 for publication as an RTD Technical Documentary Report.

The author acknowledges the assistance of Messrs. W. V. Bertram, C. D. Geisler, and C. J. Windisch, in recording the data and in the experimental work and Mr. V. Hopkins for his helpful suggestions.

This technical documentary report has been reviewed and is approved.

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ABSTRACT

Liquid metals have certain properties that make them candidates for heat transfer use in aerospace systems. The objective of this investigation was to determine the magnitude of the heat transfer coefficient of condensation for sodium. Design factors and program organization are discussed, and a description of the equipment is presented. The heat transfer experiments were conducted in a closed boiler system, in which the sodium was boiled in the lower region and condensed upon an instrumented surface in the upper region. Operational techniques and history are discussed, including the massive, premature failure of the condensing section. The 1700°F sodium leaked into the 500°F cooling air passage and generated a considerable amount of dense smoke before complete shut-down of the equipment. Only three data points were obtained. The heat transfer coefficients for condensing sodium ranged from 79.8 to 473.6 Btu/hr-ft^2-°F for heat fluxes of 7,683 to 24,083 Btu/hr-ft^2. A sample calculation is presented. The boiler material showed satisfactory corrosion resistance to sodium but not to the sodium and air reaction. Differential thermal expansion apparently loosened the special surface thermocouples, allowing the sodium to leak into the coolant passage.

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

I. INTRODUCTION

Liquid metals have certain properties, such as heat capacity, thermal conductivity, and thermal stability, that make them attractive candidates for use as working fluids and/or heat transfer fluids in aerospace systems. Working fluids receive energy from a heat source, such as a nuclear reactor or a solar collector, and transmit this energy to a prime mover, such as a turbine. Heat transfer fluids receive energy from a heat source and transmit this energy to another location or medium, either for use, as in a heat exchanger, or for rejection, as in a space radiator.

High heat capacity and thermal conductivity allow liquid metals to transfer more energy than other more common heat transfer materials. Liquid metals also have good thermal stability, with operating temperature limitations being introduced by the materials used to contain them. Higher operating temperatures, possible because of the thermal stability, would allow greater system operating efficiency. Greater operating efficiency in any system of an aerospace vehicle is always desirable. If liquid metals are to be used in aerospace systems, they must be studied to determine the magnitude of their heat transfer properties.

This investigation was concerned with the heat transfer properties associated with the condensation of sodium. The primary objective of this work was the determination of the magnitude of the heat transfer coefficient for condensing sodium vapor under various operating conditions of pressure, temperature, and heat flux. A secondary objective, established early in the program and subsequently discarded, was the determination of the mode of condensation, whether the condensate was formed in a continuous film or in drops.

The heat transfer measurements required for the determination of the coefficient of condensation were made in a closed boiler system. The boiler was a large cylinder, closed at both ends, in which a smaller cylindrical surface was located. The sodium vapor, generated in the larger cylinder by boiling the sodium, was condensed upon the outer surface of the smaller closed cylinder. This condensing surface was instrumented to obtain surface temperature measurements. The condensate then returned to the boiling region to complete the operating cycle. Observation of the condensing surface during operation was to allow the mode of condensation to be determined.

II. BACKGROUND

Several factors were considered in establishing design requirements for an apparatus that would generate and contain liquid metal vapor for condensation experiments. Among these factors were the following:

1. Geometry and orientation of the condensing surface;

2. Temperature range of operation; and

3. Pressure range.

A concentric cylindrical configuration was selected to insure symmetry in the vapor-condensate flow path. Vertical orientation was selected to insure uniform vapor envelopment of the condensing surface.

The original plan included studying various liquid metals at temperatures to 2500°F. The upper limit was established to cover the expected operating range of sodium, the liquid metal of prime concern. This material is solid at room temperature, and no heat transfer studies of the solid material were planned.

A pressure range of 0.1 mm. Hg abs. to 65 psia was selected for this apparatus. The low pressure was established as an aid for outgassing volatile contaminants in the liquid metal. The 65 psia stipulation was established to accommodate any pressure surges that might occur during boiling.

The determination of the mode of condensation (continuous film or dropwise) was originally established as a secondary experimental objective. This objective was discarded because there were many problems associated with viewing the condensate and sealing the windows. Solving these problems would have required more effort than was allotted to the entire program. The viewing ports were not removed from the design.

The investigation was divided into three steps:

1. The design, fabrication, and operation of a small boiler (2 in. diameter by 10 in. high) with sodium and rubidium to determine design concepts for a larger boiler and establish techniques for handling liquid metals.

2. The design, fabrication, and operation of a larger experimental boiler (6 in. diameter by 21 in. high) to 1800°F to determine the heat transfer coefficients for condensing sodium.

3. The fabrication of another boiler, based upon the design of the boiler of Step 2 but constructed from special high temperature metals, and its operation to determine the heat transfer coefficients for several condensing liquid metals to 2500°F.

Step 1 has been completed and the results have been reported (Refs. 1-3). Some data for the over-all heat transfer coefficients were determined for sodium and rubidium condensing on a small stainless steel U-tube. Various condensing heat rates were used with heat flux levels ranging from 783 to 9,623 Btu/hr-ft^2. The over-all heat transfer coefficients* determined for sodium during the last part of Step 1 ranged from 6.1 to 23.5 Btu/hr-ft^2-°F; and for rubidium the values ranged from 8.2 to 20.6 Btu/hr-ft^2-°F.

Step 2 has been completed and the results have been reported (Refs. 4-6). In the preliminary work (Ref. 4), the heat transfer coefficients for condensing sodium ranged from 0.6 to 946 Btu/hr-ft^2-°F. The low values and extreme range of values reflected the heat transfer of a varying mixture of sodium vapor and argon. The heat flux established in the condensing area ranged from 177 to 35,428 Btu/hr-ft^2. In the supplementary work (Ref. 5), the heat transfer coefficients for condensing sodium (with the argon removed) ranged from 65.9 to 951.6 Btu/hr-ft^2-°F. The heat flux levels ranged from 3,977 to 37,925 Btu/hr-ft^2 at sodium vapor temperatures from 1332 to 1791°F.

Step 3 has been terminated and the results are presented in this report.

III. SODIUM BOILING SYSTEM

A. Boiler Description

A pictorial representation of the boiler used for these experiments is shown in Figure 1. As the liquid metal in the lower region was boiled, the vapor filled the upper region and surrounded the centrally-located cylindrical condensing surface. The liquid metal condensed on the outer skin of this condensing surface when heat was removed from the inner skin by the cooling air. The condensate then returned to the boiling region to complete the operating cycle.

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* The over-all heat transfer coefficient included the condensation of the metal vapor, metal vapor-liquid interface resistance, liquid thermal conductivity, liquid-condensing surface interface resistance, condenser material conductivity, and solid-gas resistance as the heat was removed by the cooling air.

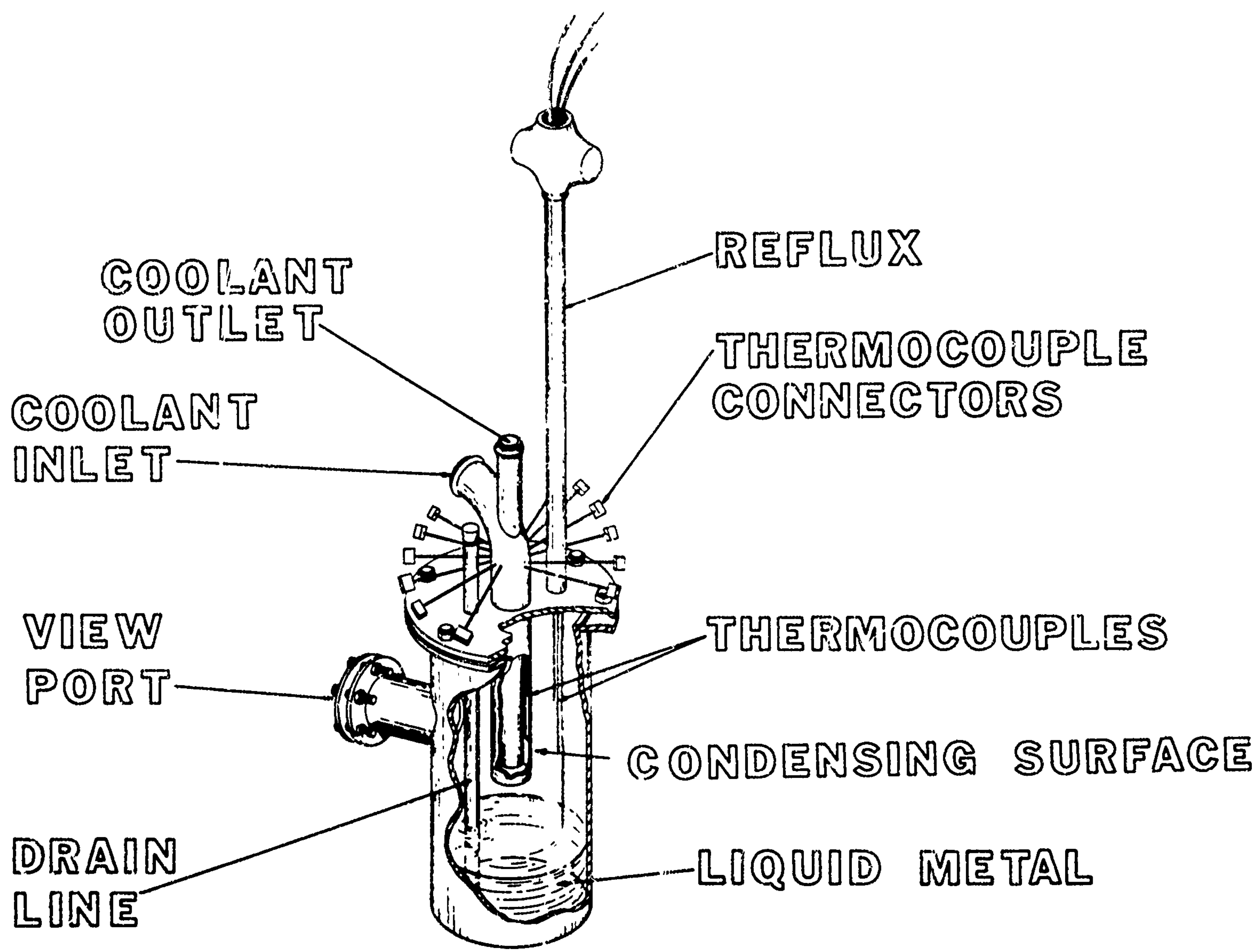

Figure 1 - Boiler Pictorial Representation

The actual boiler used for these experiments is shown in Figure 2. This boiler was made from Haynes 25, a high temperature alloy with the following composition:

Elements	Percentage
Nickel	9-11
Chrome	19-21
Tungsten	14-16
Iron	3. maximum
Carbon	0.05-0.15
Silicon	1. maximum
Manganese	1-2
Cobalt	Balance (approx. 50)

This material was selected for its strength at temperatures of 2300°F and higher. The Haynes 25 also did not require an inert gas shield for protection from oxidation at these operating temperatures.

The boiler body was made from 0.5 in. plate rolled and welded into a cylinder of 6.754 outside diameter. The boiler bottom was a 0.375 in. thick disc welded into the body. The boiler top, made from a 0.875 in. thick, 11 in. diameter disc, was bolted to a ring that was welded to the boiler body.

The three portholes were included in the design to allow illumination and visual examination of the condensation process. These portholes are shown in Figure 2. During this operation, the portholes were sealed with Type 347 stainless steel discs, using Inconel X nonplated hollow metal "O" rings as seals.

Access to the boiler interior, required for post-operative cleaning and inspection, was through the bolted top. The original flanged top was sealed with a taper fit, but this seal was modified to include two Inconel X nonplated "O" ring seals of identical cross-section, one with a 6.25 in. diameter and the other with a 6.75 in. diameter. The original configuration, using the taper fit, was found to be unsatisfactory. Also, previous experience with boilers sealed with one "O" ring showed that failure of the "O" ring seal was the reason for halting boiler operation. With the two metallic "O" ring seals installed, the outer seal was still effective when the inner one failed after prolonged exposure to sodium vapor.

A drain line was made from 0.25 in. diameter schedule 40 pipe. The difficulties of fabrication with Haynes 25 made it necessary to weld short pieces of the pipe together to form the required over-all length. The drain line extended to within 0.25 in. of the boiler bottom. The boiler was to be drained by pressurizing the interior with argon, forcing the liquid metal out

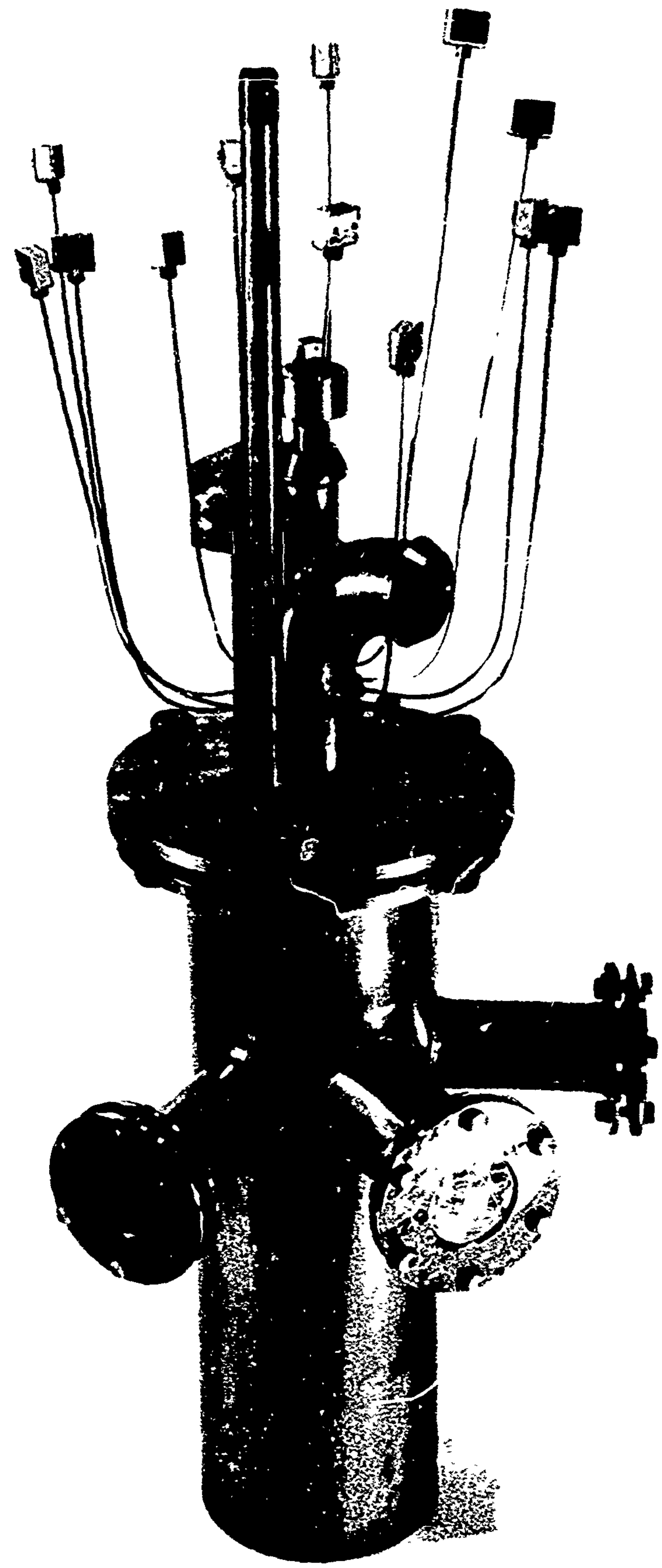

Figure 2 - Haynes 25 Boiler, Front View

through the drain line into storage containers. This line, topped with a packless valve of Haynes 25 material, is partially hidden in Figure 2.

The boiler is shown in Figure 3 as it looked after 72 hr. of operation. The drain line was bent to allow the packless valve to be removed. The block at the top of the figure, on the reflux condenser, was for transducer access to the boiler interior. The pressure measuring system was connected to one of the three outlets. Four sheathed thermocouples were inserted in the top outlet of this block and extended through the reflux condenser into the vapor and liquid phases of the liquid metal in the boiler. The third outlet was not used during the operation.

B. Condensing Surface

Accurate temperature measurement is essential for any heat transfer experiment. The condensing surface temperature and the vapor temperature must be determined accurately so that errors are minimized. In this work, the temperature difference between the liquid metal vapor and the condenser surface was found to be quite critical to the results of these experiments.

Temperatures on the condensing surface were measured by eight surface thermocouples. Four additional thermocouples were located behind the condensing surface (on the inside of the tube). The locations of the thermocouples are shown in Figure 4. The twelve thermocouple leads extend outward and then upward from the condensing tube, as shown in Figures 2 and 3. The eight surface thermocouple junctions mounted in the condensing surface were made by pressing the thermocouple sheaths through the tube, wedging the ends of the wires together, and then smearing the leads into the surface itself by a rough-grinding operation. These thermocouples indicated only the surface temperature; the thermocouple junction thickness was less than 0.001 in.

The condensing surface thermocouple leads were structurally reinforced by the addition of the attachment ring also shown in Figure 3. Each thermocouple lead was attached to this Nichrome wire ring before operation began.

The thermocouple materials for this boiler were Haynes 25 and Type "A" nickel. Using thermocouple sheaths and one wire of the same material as the boiler body and the condensing tube decreased the effects of thermal expansion on the force fit of the sheaths in the holes of the condensing tube. The electrical read-out of developed voltages was also assisted by the common grounding of all signals.

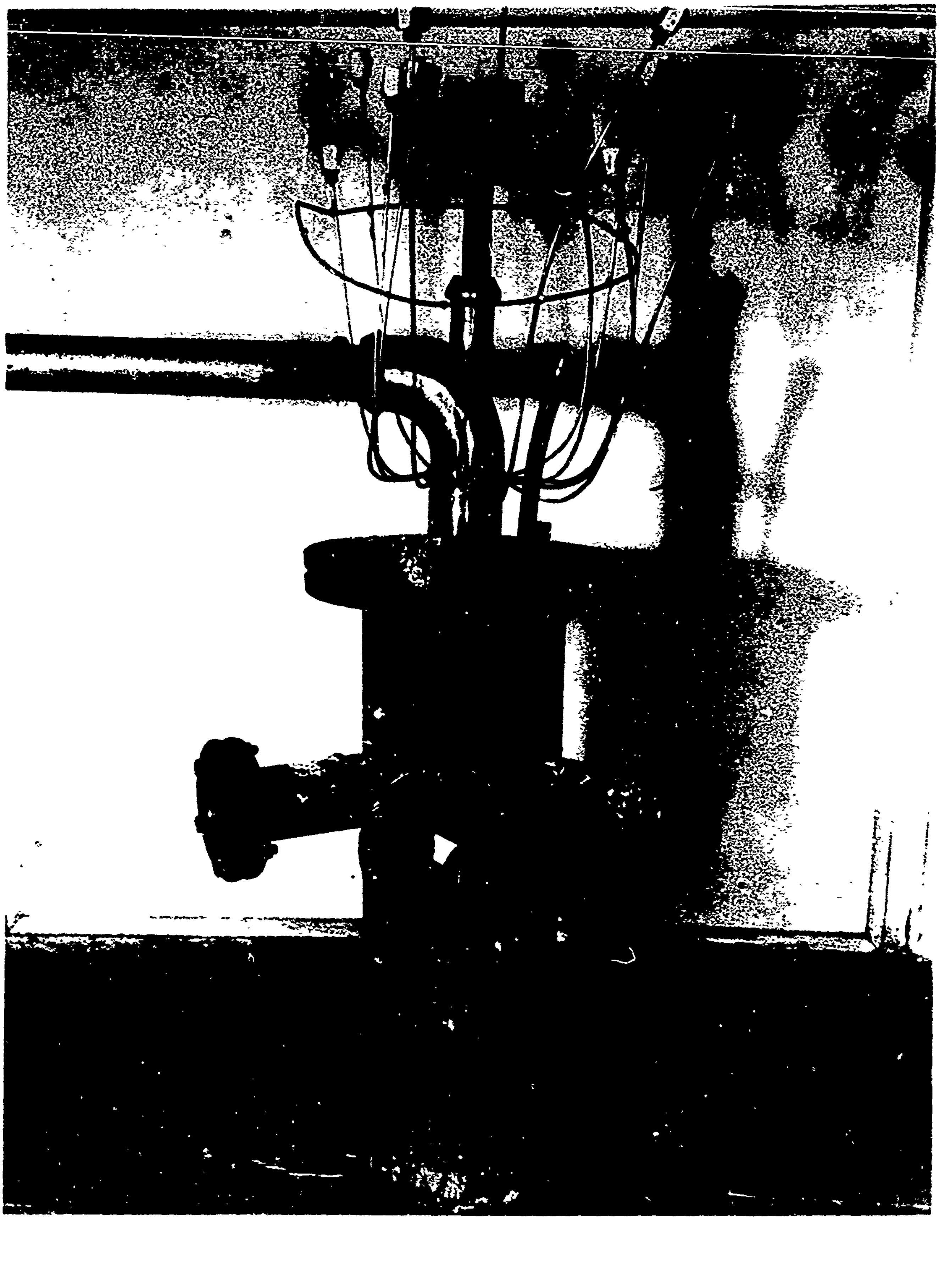

Figure 3 - Haynes 25 Boiler, After 72 Hr. of Operation

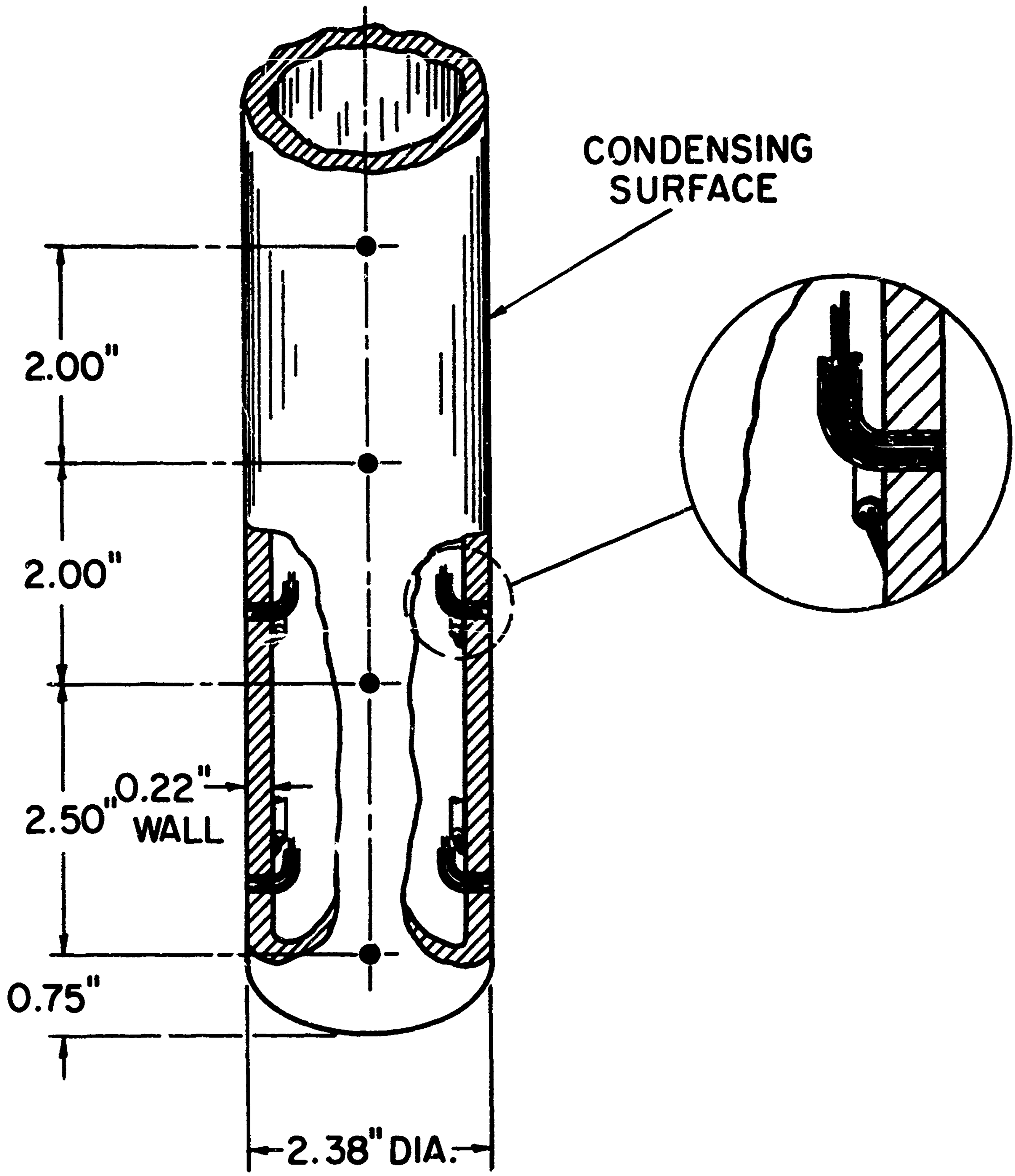

Figure 4 - Thermocouple Locations on Condensing Tube

C. Support Equipment

During these experiments, two thermocouples were used to measure the vapor temperature. They were located 0.75 in. from the condensing surface. One junction was located in the same horizontal plane as the lowest three surface thermocouples; the other junction was located 2.5 in. higher, corresponding to the plane of the other set of three surface thermocouples. These thermocouples can be seen in the pictorial representation, Figure 1.

Condenser surface and vapor temperature thermocouple outputs were measured in millivolts with a Leeds and Northrup K-3 universal potentiometer and a Leeds and Northrup DC null detector. Temperatures were then computed from a chart based on the calibration of the actual thermocouple materials, Haynes 25 and "A" nickel. The thermocouples were calibrated in an air oven using a platinum-platinum 10 per cent rhodium reference thermocouple. Part of the calibration curve for this thermocouple material combination is shown in Figure 5.

Pressure was monitored by a compound range, fluid-filled Ashcroft pressure gage and by a protected, mercury-filled manometer. The gage gave approximate pressures and showed when the manometer could be used in determining the boiler internal pressure.

Heat input control was based upon the output of a platinum-platinum 10 per cent rhodium thermocouple located in the liquid zone of the sodium. Heat input for these experiments came from a 30 kw. Ajax Magnethermic induction heater. The furnace surrounded the lower 10 in. of the boiler. The radial clearance between the boiler and the furnace was approximately 0.060 in. This clearance allowed the boiler to be easily installed and removed without sacrificing too much inductance.

Coolant air flow was indicated with a Fischer and Porter flowmeter calibrated with an American Meter Company gasometer with the actual fittings installed. Coolant inlet and outlet temperatures were sensed by standard iron-constantan thermocouples.

Closed circuit television was used to view the boiler system during operation. Sodium leakage could be observed without exposing personnel to the reaction products. The camera was focused on the top of the insulated container which surrounded the boiler. The field of view included the entire exposed length of the reflux condenser but did not include the cooling air outlet. The cooling air was exhausted at floor level, away from the boiler rig.

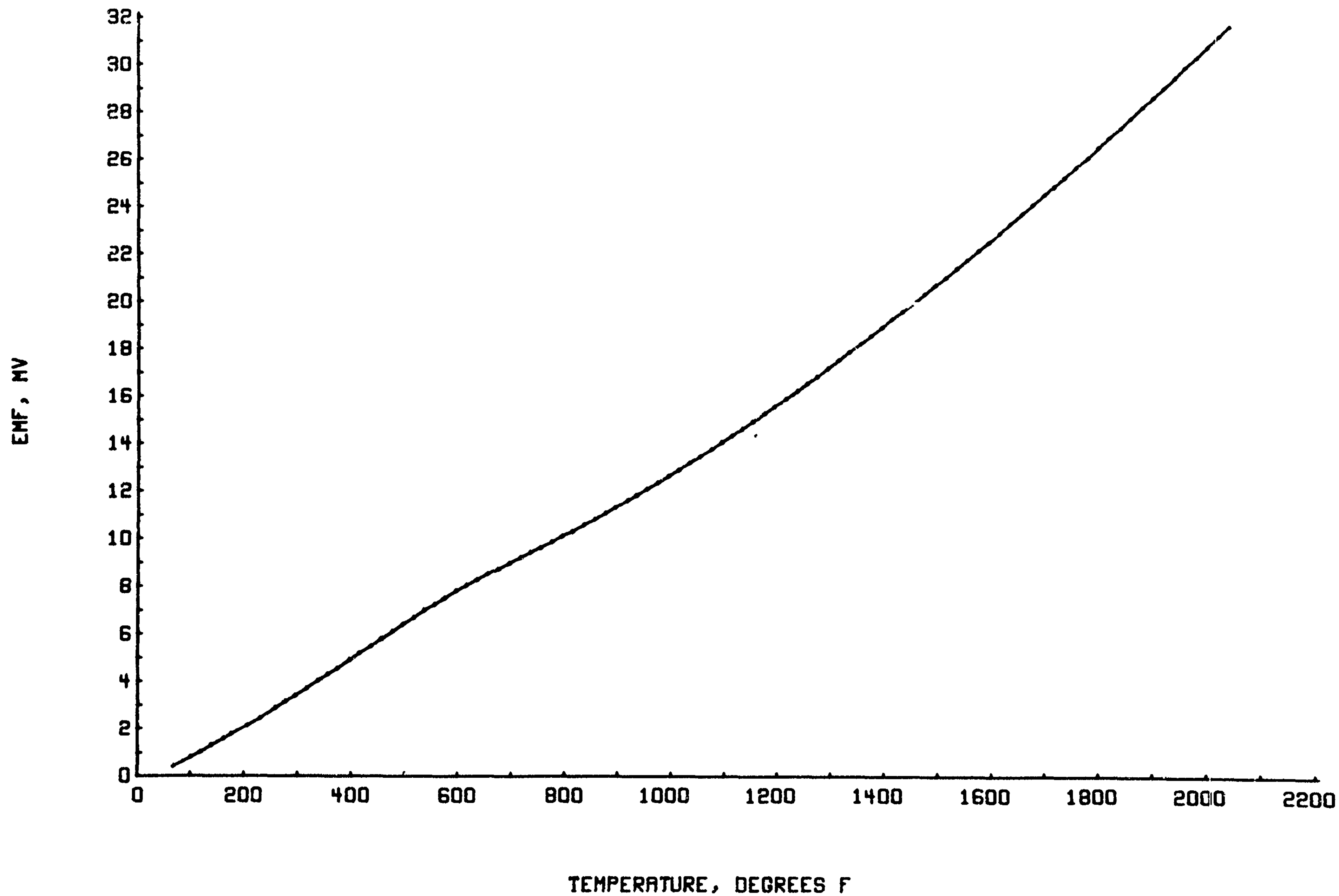

Figure 5 - Calibration Curve, Haynes 25 Vs. "A" Nickel Thermocouple

IV. SYSTEM OPERATION

A. Operational Technique

This investigation required that sodium vapor surround the condensing surface at all times. The liquid metal was boiled to produce the required vapor. Any liquid can be boiled by adding heat and/or reducing the pressure of the liquid. The boiling point of sodium under one atmosphere of pressure has been reported as 1618°F (Ref. 7). It was desired to decrease the internal pressure of the boiler and boil the sodium at a lower temperature. Removal of the argon cover gas, introduced during the boiler charging operation, would eliminate this contaminant from the system, reduce the pressure on the sodium, and permit the sodium to boil at a lower temperature. Thus, the required sodium vapor would be generated, boiler life would be improved, and the quantity of noncondensable argon vapor around the condensing surface would be minimized.

The procedure for removing the argon cover gas started by first heating the boiler to 800°F, melting the sodium, and releasing any trapped argon. Then the boiler was heated to 1200-1300°F while a laboratory vacuum pump removed the argon.

The boiler temperature was allowed to stabilize at 1300°F until the pressure also stabilized. Generally, the evacuation line became plugged with solidified sodium during this stabilization period. Plugging of the line indicated that the amount of argon remaining in the boiler was low and that the sodium vapor was being generated satisfactorily. When the line became plugged, a valve was closed, isolating the boiler system from the evacuation system.

B. Operational History

The empty boiler was first heated to 2100°F and held at that temperature for 11 hr., allowing the relaxation of any residual stresses from welding. Thermal expansion of the boiler top allowed the taper fit of the top to the body to be reduced. This expansion had been found in the previous boilers made from stainless steel (Ref. 4). Addition of the two nonplated Inconel X "O" rings and the heating pretreatment reduced leakage at the taper fit after the sodium was installed in the boiler.

The boiler, still empty, was then fully insulated and held at 1000°F for 15 additional hours. After this time, the fastening bolts holding the boiler top to the boiler body were retorqued to assure that the junction was leak-tight. A 17-hr. leak check showed no measurable leakage with 45 psig air pressure on the boiler interior.

The Haynes boiler was then charged with 3.5 lb. of sodium and subsequently heated to 800°F for 3 hr. to check system performance and to allow any argon that may have been trapped to be released from the sodium. The system checked out satisfactorily except that thermocouples 1 and 2 produced no signal. These two thermocouples were the upper two of the four that form the vertical line of thermocouples shown in Figure 4.

The boiler was then heated to 1300°F while the vacuum pump removed as much argon as possible from the boiler interior. The pressure was reduced to an indicated 0.5 cm. Hg when the evacuation line plugged with solidified sodium.

The boiler was operated at 1400°F for 28 hr. in an attempt to stabilize the condenser temperatures and boiler pressure. The pressure line plugged with solidified sodium, and considerable difficulty was encountered in trying to obtain a valid pressure measurement. Adding a replacement pressure measurement line to the boiler system eliminated the clogged line. The new line was installed into the third access port of the cross on top of the reflux condenser.

The boiler temperature was then increased to 1650°F and stabilized so that heat transfer data could be taken. One datum point was recorded and the boiler temperature was increased to 1700°F. Two more data points were recorded at different coolant air flows (corresponding to different heat flux levels). The heat input control thermocouple failed during the stabilization period for the fourth point, and the test sequence was halted for repairs.

After the defective thermocouple was replaced, the boiler was reheated to 1700°F. After approximately 20 min., smoke was observed on the television monitor. Visual examination of the test chamber disclosed that heavy, dense, white smoke of sodium dioxide was coming from the cooling air outlet tube. A failure had occurred in the condenser section that allowed the coolant air to contact the hot sodium vapor.

Normal or emergency shutdown of the boiler system previously had involved both turning off the heat source and increasing the condenser coolant air flow to remove as much heat as possible. Now, however, increasing the coolant air flow only increased the amount of smoke being generated. Some coolant flow was required to remove heat from the mass of the boiler body, but the flow had to be a compromise to restrict the amount of air coming into contact with the 1700°F sodium vapor. The boiler was cooled without producing any violent chemical reaction external to the boiler system, although the time required was considerably longer and the smoke that was generated spread throughout the building.

Postcleaning inspection revealed that the two lower surface thermocouples had failed to maintain the seal in the condenser tube wall, which separated the sodium and cooling air. It is believed that the sodium vapor leaked into the coolant passage and reacted with the cooling air, generating more heat and perpetuating the sodium leakage. Once such a condition existed, the reaction continued with considerable heat output.

The larger of the two holes that were formed in the condenser tube is shown in Figure 6. The pattern and size of the two holes are shown in Figure 7, indicating that the reaction of sodium and air had a very detrimental corrosive effect upon Haynes 25.

After the holes were inspected, the lower end of the condenser tube was sawed off. The view into the condenser is shown in Figure 8. The inner tube, a 1 in. nominal size schedule 40 pipe of 1.315 in. outside diameter and 0.133 wall thickness, had been shortened approximately 1 in. All of the thermocouple lines had been corroded, some for as much as 6 in. of their original length.

The damage to the boiler had been massive and no repairs were possible. The experiments were terminated.

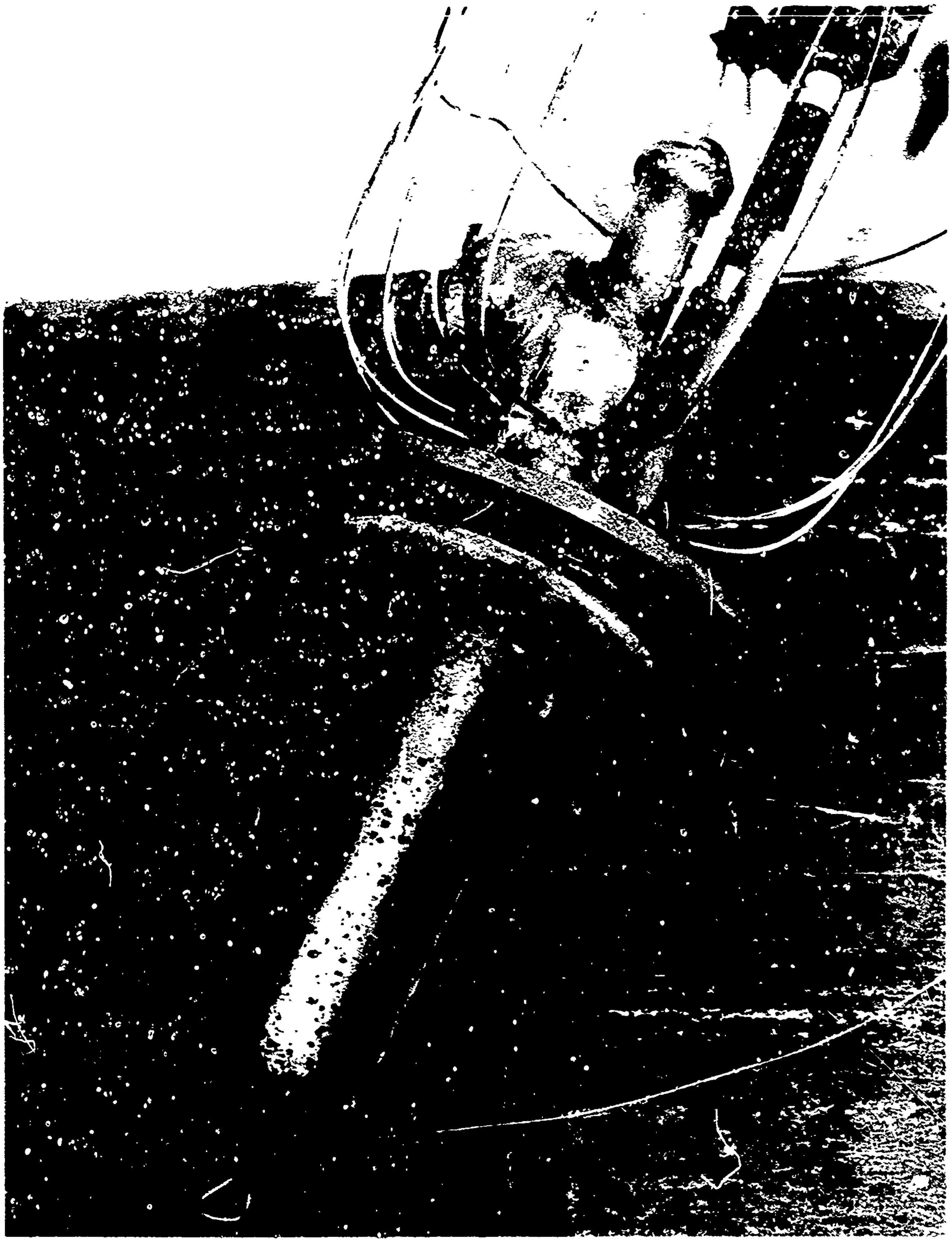

Figure 6 - Destroyed Condenser Tube, Showing One Burned Hole

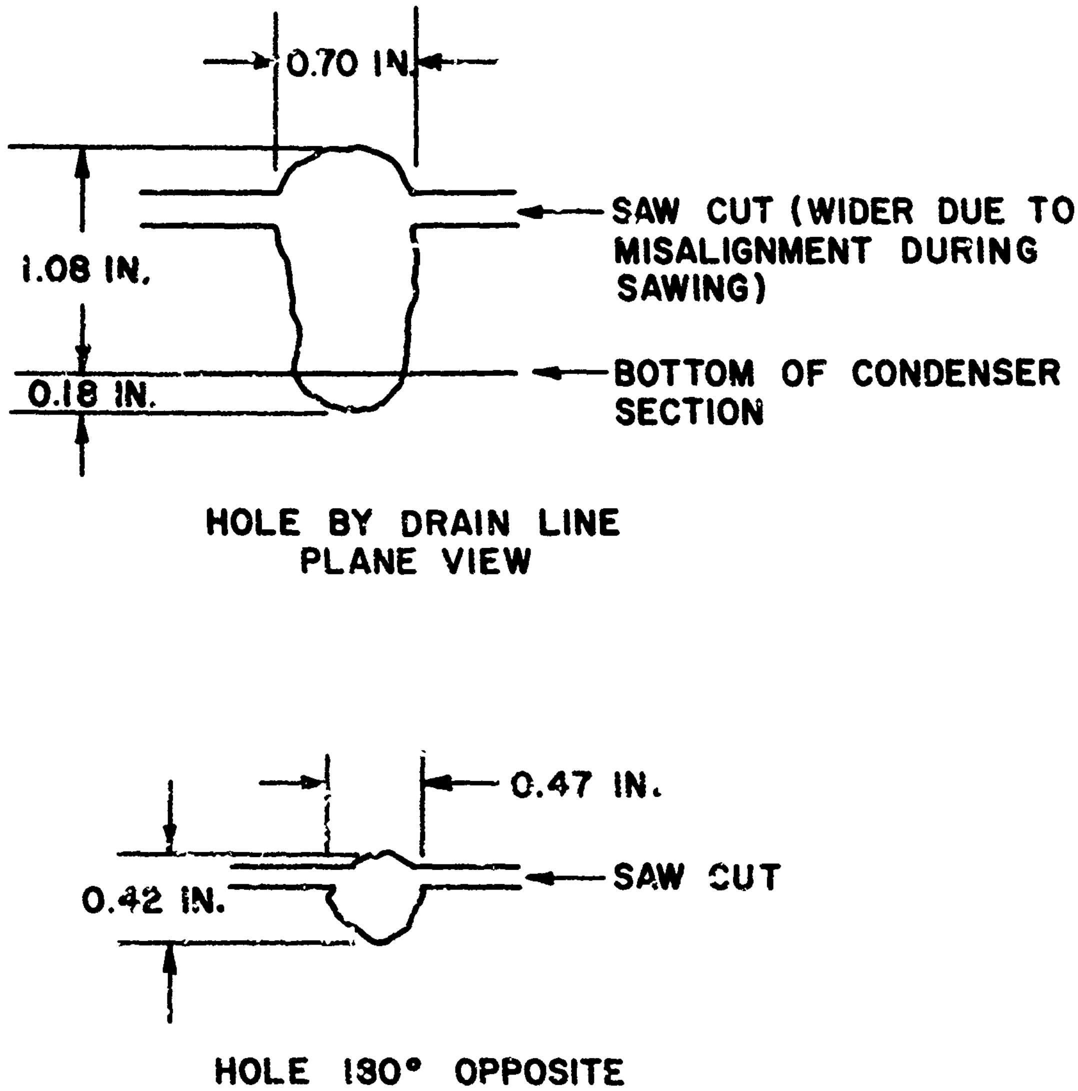

Figure 7 - Representation of the Two Burned Holes in the Condenser Tube

Figure 8 - View Looking into the Condenser Tube

V. RESULTS

A. Heat Transfer

Only three data points were obtained for the determination of the magnitude of the heat transfer coefficient for condensing sodium before the sodium-air reaction terminated the experiments. These data points are within the range of values previously reported (Ref. 5) and are as shown:

Vapor Temperature (°F)	Vapor Pressure (psia)	Heat Flux (Btu/hr-ft^2)	Heat Transfer Coefficient (Btu/hr-ft^2-°F)
1650.0	17.57	7,683	345.3
1698.1	20.57	7,886	79.8
1703.7	21.07	24,083	473.6

The measured values of vapor temperature and pressures are shown in Figure 9. The curve, shown for reference, was drawn from vapor pressure data previously reported (Ref. 7). The locations of the two points below the saturated vapor pressure curve are indicative of the partial plugging of the pressure measurement line and do not represent any unusual condition within the boiler.

The heat flux values represent two of the three basic coolant air flows The input heat control thermocouple failure occurred when the highest coolant air flow was being stabilized, and no data were obtained for the high flow. Massive boiler failure occurred during the next attempt to establish the high coolant air flow and no further operation was possible.

The values for the heat transfer coefficients were determined by the process discussed in Appendix A. These three points are within the range of values previously reported and do not show any significant trend toward reaching the high values that have been predicted and expected. The higher vapor temperatures expected from the operation of this boiler were not obtained, nor were the higher values of the heat transfer coefficient for condensing sodium obtained. The unreduced data are presented in Appendix B, Table 1.

B. Boiler Performance

The operation of this boiler has shown one interesting fact that appears to contradict the obvious massive failure of the condenser section. The fact is that the material of construction, Haynes 25, did not show any corrosive

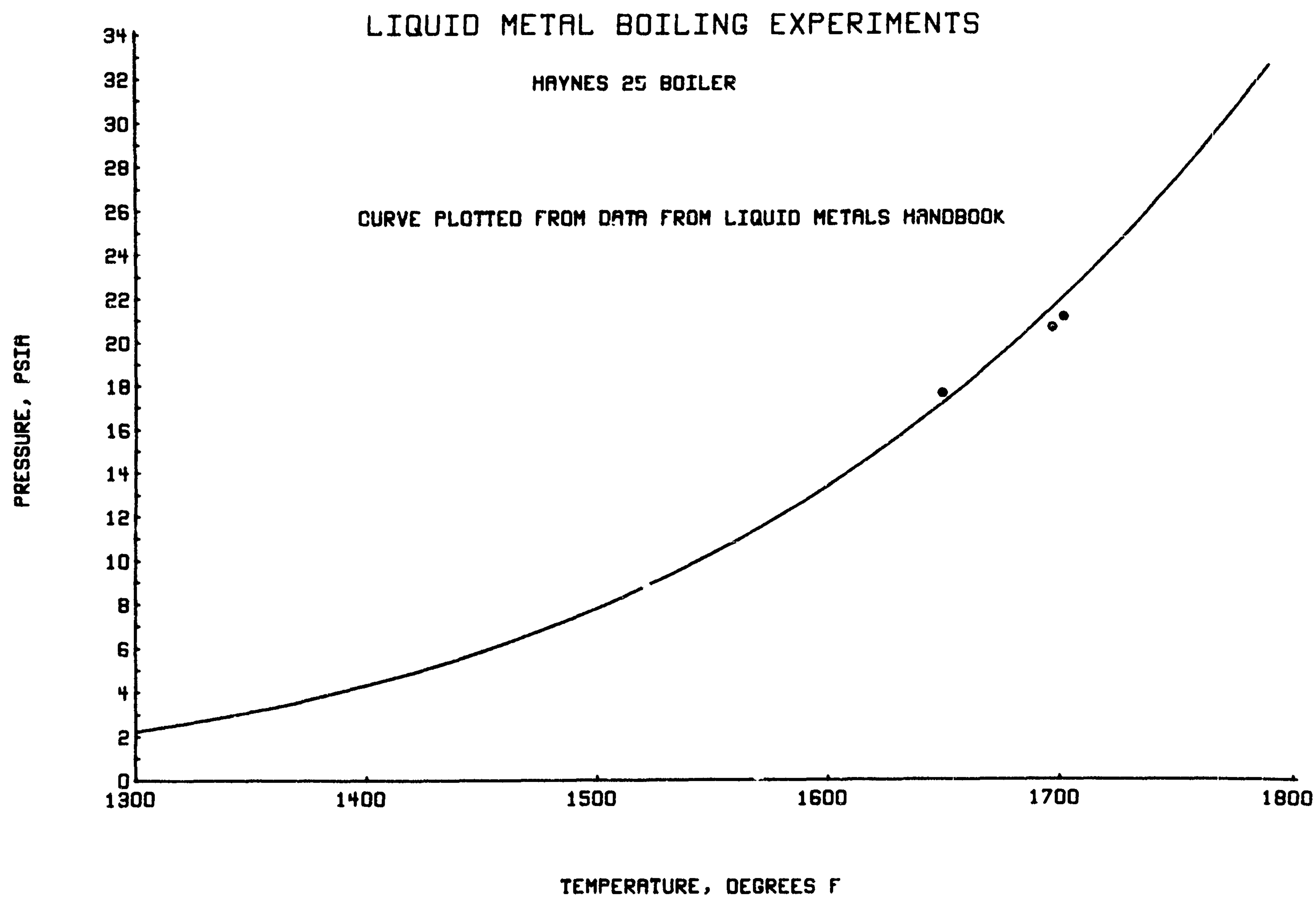

Figure 9 - Saturated Vapor Pressure Vs. Vapor Temperature - Sodium

effects from exposure to 1700°F sodium vapor. The boiler body wall, including the vertical, welded seam, was not pitted or eroded from the 46-hr. exposure to liquid and gaseous sodium. The condenser section showed discoloration from the high temperature reaction of sodium vapor and air, but the surface 1 in. away from the two holes was neither pitted nor showed other signs of corrosion.

The condenser failure and subsequent deterioration of the Haynes 25 material were not based upon the reaction of sodium and the boiler material but rather were based upon the reaction of sodium and air. This reaction generated very high temperatures (the sodium vapor temperature was approximately 1700°F and the air temperature approximately 500°F before the reaction) that could have melted the Haynes 25 and allowed the sodium to react with the molten constituents of the material. This reaction was based upon the availability of air to the sodium, and no air was present along the inner wall of the boiler body where there also was no evidence of corrosion.

The condenser failure apparently was due to a mechanical defect in the installation of the surface thermocouples or due to differential thermal expansion of the components. If the failure were due to the installation of the thermocouples, some evidence should point to this failure. However, the boiler was subjected to a 45 psig pressure check for 17 hr. before the introduction of the sodium. No leakage was evidenced by a decay in pressure during the leak test.

The failure may have been due to differential thermal expansion, even with both components being made from the same material. The thermocouple sheath and the condenser tube are both Haynes 25, but they were not necessarily at the same temperature. The cooling air passing over the small thermocouple sheaths would keep them cooler than the larger condenser tube. However, in previous work with a Type 347 stainless steel condenser that had Type 347 stainless steel thermocouples (Ref. 5), there were no troubles with leakage through the condenser section in over 539 hr. of operation on one unit. The preliminary heating of the Haynes 25 boiler to 2100°F would not have produced the same situation as normal 1700°F operation with sodium. The preliminary heating did not use sodium and there was no cooling air flow. If this heating had caused some damage, the damage would have been revealed in the 17-hr. leakage test.

The evidence points to a strain on the mechanical connection of the thermocouple sheath in the condenser tube wall. The strain was probably due to the differential expansion between the thermocouple sheath (at a temperature of approximately 700°F) and the condenser tube (at a temperature of approximately 1600°F). This strain, greater in the longer thermocouples, pulled the thermocouple sheaths enough to open a leakage path for the sodium vapor to make contact with the cooling air. The reaction was then self-perpetuating and continuously accelerated by the increasing leakage path.

VI. CONCLUSIONS

The heat transfer results obtained from these experiments are inconclusive. The abbreviated testing resulted in only three data points for vapor temperatures that have been previously studied; these three points agreed with those previously reported. The higher vapor temperatures desired to be produced from this boiler were not obtained because of the failure of the boiler condenser section.

The boiler failure appears to have been caused by a strain on the thermocouples. This strain was probably induced by the differential thermal expansion of the cooler thermocouples that were parallel to the hot condenser tube. The strain then loosened the thermocouples or otherwise generated a leakage path for the sodium through the condenser tube. This leakage allowed the sodium to contact the hot air and chemically react to form sodium dioxide.

The boiler material, Haynes 25, did not appear to be affected by the 46-hr. exposure to the sodium liquid or vapor (to temperatures of 1700°F). No corrosion was evident in the boiler body or on the condenser tube (away from the burned holes).

Any further use of the surface thermocouples similar to those used in this boiler should be preceded by a detailed study of the proposed system. This study should include differential thermal expansion analysis for relative material elongation, even when both components are made of the same material. The strength of any pressed fit junction also should be subjected to strenuous pressure tests.

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APPENDIX A

HEAT TRANSFER CALCULATIONS

The heat transfer coefficient for condensing vapor is defined (Ref. 8) as:

$$h = \frac{q}{T_s - T_w}$$

where h = heat transfer coefficient, Btu/hr-ft^2-°F

q = heat flux, Btu/hr-ft^2

T_s = vapor saturation temperature, °F

T_w = condensing wall temperature, °F

The average heat flux through the film of condensate is equal to the heat removed through the condensing surface divided by the area of the condensing surface. The heat removed through the condensing surface is the energy transmitted to the cooling air, and this value can be determined.

The mass rate of air flow through the condenser section is equal to the mass rate of flow through the flowmeter. The recorded values must be converted to standard conditions and the flowmeter reading must be corrected to the actual flowmeter calibrated reading.

The pressure of the air at the flowmeter was:

$$p = p_a + p_{gage}$$

$$p = 73.80 \text{ cm. Hg} \left(\frac{27.85 \text{ lb/ft}^2}{\text{cm. Hg}}\right) + 0.7 \text{ in. Hg} \left(\frac{70.73 \text{ lb/ft}^2}{\text{in. Hg}}\right)$$

$$p = (2055.3 + 49.5) \text{ lb/ft}^2 = 2104.8 \text{ lb/ft}^2$$

The calibrated flowmeter reading conversion gives the volume of flow:

$$4.0 \text{ cfm (measured)} = 3.989 \text{ ft}^3/\text{min}$$

The absolute air temperature was:

$$T = (80 + 460)°R = 540°R$$

From the perfect gas law comes the mass rate of air flow:

$$m = \frac{pV}{RT}$$

$$m = \frac{\left(2104.8 \text{ lb/ft}^2\right)\left(\frac{3.989 \text{ ft}^3}{\text{min.}}\ \frac{1 \text{ min.}}{60 \text{ sec.}}\right)}{\frac{53.3 \text{ ft}}{°R}\quad 540°R}$$

$$m = 0.004862 \text{ lb/sec}$$

The rate of heat removal can now be calculated from the relationship:

$$Q = mc_p\Delta t$$

where

Q = rate of heat removal

m = mass air flow

c_p = specific heat of air at constant pressure

Δt = temperature increase through the cooling area

The value for the specific heat at constant pressure, c_p , is determined at the average cooling air temperature.

$$T_{avg} = \left(\frac{105 + 940}{2}\right) °F = 522.5°F$$

c_p at $522.5°F = 0.2477$ Btu/lb-°F (Ref. 9)

Therefore:

$$Q = mc_p \Delta t$$

$$Q = \left(\frac{0.004862 \text{ lb.}}{\text{sec.}}\right)\left(\frac{0.2477 \text{ Btu}}{\text{lb-°F}}\right) (940 - 105)°\text{F}$$

$$Q = 1.0056 \text{ Btu/sec} = 3620.2 \text{ Btu/hr}$$

The condensing surface area comes from the relationship and dimensions:

$$A = \pi dl + \frac{\pi}{4} d^2$$

$$A = \pi(2.375 \text{ in.}) (8.5 \text{ in.}) + \frac{\pi}{4} (2.375 \text{ in.})^2$$

$$A = 67.851 \text{ in.}^2 = 0.47119 \text{ ft.}^2$$

The heat flux through the condensate film can now be computed:

$$q = \frac{3620.2 \text{ Btu/hr}}{0.47119 \text{ ft}^2}$$

$$q = 7683.1 \text{ Btu/hr-ft}^2$$

Two vapor temperature measurements were made before the condensing wall temperatures were read and two vapor temperature measurements were made after the condenser measurements, the difference being the change in temperature during the time of the experiment. The average of these four values of the vapor saturation temperature is:

$$T_s = \frac{(1650 + 1651.5 + 1647 + 1651.5)°\text{F}}{4}$$

$$T_s = 1650.00°\text{F}$$

Only four thermocouples remained operative at the time the condensing wall temperatures were determined. The average of these four values of the condensing wall temperature is:

$$T_w = \frac{(1624 + 1626.5 + 1626.5 + 1634)°\text{F}}{4}$$

$$T_w = 1627.75°\text{F}$$

The heat transfer coefficient for condensing sodium vapor can be determined:

$$h = \frac{q}{T_s - T_w}$$

$$h = \frac{7683.1 \text{ Btu/hr-ft}^2}{(1650.00 - 1627.75)^\circ\text{F}}$$

$$h = 345.3 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

The boiler internal pressure is also determined:

$$p_b = 3.3 \text{ psig} + p_a$$

$$p_b = 3.3 \text{ lb/in}^2 + 73.80 \text{ cm. Hg} \left(\frac{0.1934 \text{ lb/in}^2}{\text{cm. Hg}}\right)$$

$$p_b = 3.3 \text{ lb/in}^2 + 14.27 \text{ lb/in}^2 = 17.57 \text{ lb/in}^2$$

APPENDIX B

TABLE 1

UNREDUCED DATA FROM THE EXPERIMENTS

Vapor Temperature, as listed in Results, °F	1650.0	1698.1	1703.7
Automatic Control Setting, °F	1700	1750	1750
Heat Input Power, %	45.0	59.0	60.0
Boiler Pressure, psig	3.3	6.3	6.8
Barometric Pressure, cm. Hg abs.	73.80	73.80	73.80
Condenser Air Flow, indicated cfm	4.0	4.0	11.1
Flow Measurement, Air Pressure, in. Hg gage	0.7	0.7	5.7
Flow Measurement, Air Temperature, °F	80	80	79
Coolant Temperature, Inlet, °F	105	126	103
Coolant Temperature, Outlet, °F	940	980	870
Condenser Temperature, °F			
Left, Upper	1624	1599	1661
Left, Lower	1626.5	1599.2	1638.1
Right, Upper	1626.5	*	*
Right, Lower	1634	1599.5	1659.6
Vapor Temperature, °F			
Low, Before	1650	1699	1709.5
Low, After	1647	1696.5	1699.5
High, Before	1651.5	1704	1708
High, After	1651.5	1693	1698
Liquid Temperature, °F			
Before	1673	1728.5	1714.5
After	1665	1729.5	1704.5

* Thermocouple developed no voltage, assumed to be burned out.

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13 ABSTRACT

Liquid metals have certain properties that make them candidates for heat transfer use in aerospace systems. The objective of this investigation was to determine the magnitude of the heat transfer coefficient of condensation for sodium. Design factors and program organization are discussed, and a description of the equipment is presented. The heat transfer experiments were conducted in a closed boiler system, in which the sodium was boiled in the lower region and condensed upon an instrumented surface in the upper region. Operational techniques and history are discussed, including the massive, premature failure of the condensing section. The 1700°F sodium leaked into the 500°F cooling air passage and generated a considerable amount of dense smoke before complete shut-down of the equipment. Only three data points were obtained. The heat transfer coefficients for condensing sodium ranged from 79.8 to 473.6 Btu/hr-ft^2-°F for heat fluxes of 7,683 to 24,083 Btu/hr-ft^2. A sample calculation is presented. The boiler material showed satisfactory corrosion resistance to sodium but not to the sodium and air reaction. Differential thermal expansion apparently loosened the special surface thermocouples, allowing the sodium to leak into the coolant passage. (U)

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